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6. AUTHORS
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14. ABSTRACT
The objective of this research program is to provide theoretical support to the study of solid state quantum computing, with a focus on spin qubits. Our main research thrusts have been on two-spin decoherence, few-spin manipulation, and spin communication. On two-spin decoherence, we calculated phonon and nuclear spin induced dephasing, and spin-orbit and hyperfine induced relaxation. On

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Report Title

Theoretical study of solid state quantum information processing

ABSTRACT

The objective of this research program is to provide theoretical support to the study of solid state quantum computing, with a focus on spin qubits. Our main research thrusts have been on two-spin decoherence, few-spin manipulation, and spin communication. On two-spin decoherence, we calculated phonon and nuclear spin induced dephasing, and spin-orbit and hyperfine induced relaxation. On few-spin manipulation, we studied a three-spin state transfer protocol, and explored three-spin encoding that allows full electrical control. On spin communication, we calculated spin-photon coupling in a co-planar waveguide, and studied spin relaxation of a moving but confined electron. In addition to these three main research directions, we have also studied hyperfine interaction in Si, valley properties in Si, nuclear spin dynamics in self-organized quantum dots, and electrically driven spin resonance for one and two spins.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
08/28/2013	24.00	Sangchul Oh, Yun-Pil Shim, Jianjia Fei, Mark Friesen, Xuedong Hu. Resonant adiabatic passage with three qubits, Physical Review A, (02 2013): 0. doi: 10.1103/PhysRevA.87.022332
08/28/2013	30.00	Peihao Huang, Xuedong Hu. Spin qubit relaxation in a moving quantum dot, Physical Review B, (08 2013): 0. doi: 10.1103/PhysRevB.88.075301
08/28/2013	29.00	Lukasz Cywinski, Xuedong Hu, S. Das Sarma, Jo-Tzu Hung. Hyperfine interaction induced dephasing of coupled spin qubits in semiconductor double quantum dots, Physical Review B, (08 2013): 0. doi: 10.1103/PhysRevB.88.085314
08/28/2013	28.00	Ting Yu, WenXian Zhang, XueDong Hu, JianQiang You, ZeLiang Xiang. Implementing a topological quantum model using a cavity lattice, Science China Physics, Mechanics and Astronomy, (07 2012): 0. doi: 10.1007/s11433-012-4864-9
08/28/2013	27.00	Yun-Pil Shim, Sangchul Oh, Jianjia Fei, Xuedong Hu, Mark Friesen. Probing quantum phase transitions in a spin chain with a double quantum dot, Physical Review B, (04 2013): 0. doi: 10.1103/PhysRevB.87.155405
08/28/2013	26.00	Rui Li, Xuedong Hu, J. Q. You. Controllable exchange coupling between two singlet-triplet qubits, Physical Review B, (11 2012): 0. doi: 10.1103/PhysRevB.86.205306
08/28/2013	25.00	Jianjia Fei, Dong Zhou, Yun-Pil Shim, Sangchul Oh, Xuedong Hu, Mark Friesen. Mediated gates between spin qubits, Physical Review A, (12 2012): 0. doi: 10.1103/PhysRevA.86.062328
08/30/2011	4.00	Massoud Borhani, Xuedong Hu. Two-spin relaxation of P dimers in silicon, Physical Review B, (12 2010): 241302. doi: 10.1103/PhysRevB.82.241302
08/30/2011	5.00	Lucy V.C. Assali, Helena M. Petrilli, Rodrigo B. Capaz, Belita Koiller, Xuedong Hu, Sankar Das Sarma. Hyperfine interactions in silicon quantum dots, Physical Review B, (4 2011): 165301. doi: 10.1103/PhysRevB.83.165301
08/30/2011	6.00	Xuedong Hu. Two-spin dephasing by electron-phonon interaction in semiconductor double quantum dots, Physical Review B, (4 2011): 165322. doi: 10.1103/PhysRevB.83.165322
08/30/2011	7.00	Yun-Pil Shim, Sangchul Oh, Xuedong Hu, Mark Friesen. Controllable Anisotropic Exchange Coupling between Spin Qubits in Quantum Dots, Physical Review Letters, (5 2011): 180503. doi: 10.1103/PhysRevLett.106.180503
08/30/2011	8.00	Sangchul Oh, Mark Friesen, Xuedong Hu. Even-odd effects of Heisenberg chains on long-range interaction and entanglement, Physical Review B, (10 2010): 140403. doi: 10.1103/PhysRevB.82.140403
08/30/2011	9.00	Dimitrie Culcer, Lukasz Cywinski, Qiuzi Li, Xuedong Hu, Sankar Das Sarma. Quantum dot spin qubits in silicon: Multivalley physics, Physical Review B, (10 2010): 155312. doi: 10.1103/PhysRevB.82.155312
08/30/2011	10.00	Dimitrie Culcer, Xuedong Hu, Sankar Das Sarma. Interface roughness, valley-orbit coupling, and valley manipulation in quantum dots, Physical Review B, (11 2010): 205315. doi: 10.1103/PhysRevB.82.205315
08/31/2012	15.00	Lian-Ao Wu, Yun-Pil Shim, Sangchul Oh, Jianjia Fei, Mark Friesen, Xuedong Hu. Heisenberg spin bus as a robust transmission line for quantum-state transfer, Physical Review A, (08 2011): 0. doi: 10.1103/PhysRevA.84.022330

08/31/2012	16.00	A. Saraiva, Belita Koiller, Xuedong Hu, S. Das Sarma, Dimitrie Culcer. Valley-Based Noise-Resistant Quantum Computation Using Si Quantum Dots, Physical Review Letters, (03 2012): 0. doi: 10.1103/PhysRevLett.108.126804
08/31/2012	17.00	A. Saraiva, M. Calderón, Rodrigo Capaz, Xuedong Hu, S. Das Sarma, Belita Koiller. Intervalley coupling for interface-bound electrons in silicon: An effective mass study, Physical Review B, (10 2011): 0. doi: 10.1103/PhysRevB.84.155320
08/31/2012	18.00	Xuedong Hu, Massoud Borhani. Spin manipulation and relaxation in spin-orbit qubits, Physical Review B, (03 2012): 0. doi: 10.1103/PhysRevB.85.125132
08/31/2012	19.00	Zhan Shi, C. Simmons, J. Prance, John Gamble, Teck Koh, Yun-Pil Shim, Xuedong Hu, D. Savage, M. Lagally, M. Eriksson, Mark Friesen, S. Coppersmith. Fast Hybrid Silicon Double-Quantum-Dot Qubit, Physical Review Letters, (04 2012): 0. doi: 10.1103/PhysRevLett.108.140503
08/31/2012	21.00	John King Gamble, Mark Friesen, S. Coppersmith, Xuedong Hu. Two-electron dephasing in single Si and GaAs quantum dots, Physical Review B, (7 2012): 0. doi: 10.1103/PhysRevB.86.035302
08/31/2012	22.00	Yu-xi Liu, Franco Nori, Xuedong Hu. Strong coupling of a spin qubit to a superconducting stripline cavity, Physical Review B, (07 2012): 0. doi: 10.1103/PhysRevB.86.035314
08/31/2012	23.00	Sangchul Oh, Yun-Pil Shim, Jianjia Fei, Mark Friesen, Xuedong Hu. Effect of randomness on quantum data buses of Heisenberg spin chains, Physical Review B, (06 2012): 0. doi: 10.1103/PhysRevB.85.224418

TOTAL: **22**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. Invited talk, Si Qubit workshop, Berkeley, California, August, 2009.

2. Invited talk, International Workshop on Dynamical Decoupling, Boulder, Colorado, October, 2009.

3. Seminar, Quantum Information Science Program, Kavli Institute of Theoretical Physics, University of California at Santa Barbara, Santa Barbara, California, November, 2009.

4. Invited talk, The 5th Cross-Strait and International Conference on Quantum Manipulation, Beijing, China, December, 2009.

5. Nine contributed talks, The American Physical Society March Meeting, Portland, Oregon, March 2010.

6. Invited talk, Quantum Information Processing with Spins and Superconductors (QISS10), Waterloo, Canada, May, 2010.

7. Invited talk, The 10th Workshop on Quantum Engineering and Physics, Guangzhou, China, June, 2010.

8. One contributed talk and two posters, International Conference on Physics of Semiconductors, Seoul, Korea, July, 2010.

9. Contributed talk, Si Qubit workshop, Albuquerque, New Mexico, August, 2010.

10. Seminar, Basque Country University, Bilbao, Spain, September, 2010.

11. Invited talk, The 6th Cross-Strait and International Conference on Quantum Manipulation, Beijing, China, December, 2010.

12. Invited talk, and concluding remarks, The 4th International Workshop on Solid State Quantum Computing, Shanghai, China, December, 2010.

13. Five contributed talks, The American Physical Society March Meeting, Dallas, Texas, March, 2011.

14. Two seminars, Quantum Open System Frontiers: Entanglement, Decoherence and Control Program, Kavli Institute of Theoretical Physics (KITPC), Beijing, China, April, 2011.

15. Two seminars, Atomic physics using superconducting circuits Program, KITPC, Beijing, China, June, 2011.

16. Contributed talk, Si Qubit workshop, Denver, Colorado, August, 2011.

17. Seminar, Stevens Institute of Technology, Hoboken, NJ, October, 2011.

18. Seminar, University of Wisconsin, Madison, WI, November, 2011.

19. Invited talk, The 5th International Workshop on Solid State Quantum Computing, Hong Kong, China, December, 2011.

20. Two contributed talks, Si Qubit Workshop, Sydney, Australia, February, 2012.

21. Invited talk, The APS March Meeting, Boston, Massachusetts, March, 2012.

22. Six contributed talks, The APS March Meeting, Boston, Massachusetts, March, 2012.

23. Seminar, Princeton University, Princeton, NJ, March, 2012.

24. Invited talk, Stevens Symposium on Quantum Open System and Quantum Information, Hoboken, NJ, May, 2012.

25. Two seminars, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil, May, 2012.

26. Invited talk, The 3rd International Workshop on Entanglement, Decoherence and Quantum Control, Shanghai, China, June, 2012.

27. A contributed talk and a poster, The 31st International Conference on the Physics of Semiconductors, Zurich, Switzerland, July, 2012.

28. Colloquium, SUNY Brockport, Brockport, New York, November, 2012.

29. Colloquium, Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, Canada, December, 2012.

30.Invited talk, The 6th EMN conference, Houston, Texas, January, 2013.

Number of Presentations: 30.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

08/30/2011 13.00 Maria J. Calderon, Rodrigo B. Capaz, Xuedong Hu, Andre L. Saraiva, Sankar Das Sarma, Belita Koiller. Intervalley Coupling for Interface-Bound Electrons in Silicon: An Effective Mass Study and Insights for Qubits,
Physical Review B (06 2010)

08/30/2011 11.00 Lianao Wu, Yun-Pil Shim, Jianjia Fei, Mark Friesen, Xuedong Hu, Sangchul Oh. Heisenberg Spin Bus as a Robust Transmission Line for Quantum State Transfer,
Physical Review A (02 2011)

08/30/2011 12.00 Dimitrie Culcer, Andre Saraiva, Belita Koiller, Xuedong Hu, Sankar Das Sarma. Valley-based noise-resistant quantum computation using Si quantum dots,
Physical Review Letters (submitted) (06 2011)

08/30/2011 14.00 Sangchul Oh, Yun-Pil Shim, Mark Friesen, Xuedong Hu. Effect of Randomness on Quantum Data Buses of Heisenberg Spin Chains,
Physical Review B (12 2010)

TOTAL: **4**

Number of Manuscripts:

Books

Received	Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Chia-Wei Huang	1.00	
Jo-Tzu Hung	0.50	
FTE Equivalent:	**1.50**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Massoud Borhani	1.00
Sangchul Oh	0.20
Peihao Huang	1.00
FTE Equivalent:	**2.20**
Total Number:	**3**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Xuedong Hu	0.17	
FTE Equivalent:	**0.17**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
John Truong	0.00	physics
FTE Equivalent:	**0.00**	
Total Number:	**1**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 1.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 1.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 1.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 1.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 1.00

Names of Personnel receiving masters degrees

NAME	
Total Number:	

Names of personnel receiving PHDs

NAME	
Chia-Wei Huang	
Total Number:	1

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Summary of Research:

1. We have studied extensively the two-spin decoherence problem, including both two-spin relaxation and two-spin dephasing.

We have calculated two-spin relaxation rates in GaAs double dots due to hyperfine interaction and phonon emission. In particular, we have considered the (11) regime, where the two electrons are separated, and exchange splitting is small. This is the operating regime for the singlet-triplet qubits that are based on the S-T0 states, which are separated from the polarized triplets T+ and T- by a finite Zeeman splitting. We have studied the relaxation of the singlet to the polarized triplet state, and found that the relaxation is dominated by the piezoelectric electron-phonon interaction, and the relaxation rate is inversely proportional to the applied magnetic field , which is quite different from single spins in single-dot. At B ~ 0.1 T the relaxation rate is about 10 μs, consistent with experimental observations. We have also studied the two-spin relaxation in the spin-blockade regime, or the (02) regime (but not too deep into it). We paid particular attention to processes that can break the spin blockade, and explored the two main state crossings in the (02) regime. This work is now being written up.

We have also calculated two-electron-spin relaxation in phosphorus dimers in Si. When the two 31P nuclear spins anti-align, the two-electron singlet and triplet states are mixed, allowing relaxation through phonon emission. We have explored the regime of large exchange splitting, which is the operating regime for the Kane or Vrijen architecture of spin QC in Si. We find that the relaxation rate is proportional to J^n, where the exponent n is between 1 and 3, and modified by Coulomb interaction. Similar to the exchange splitting J, depends sensitively on the position of the 31P nuclei. For example, when two 31P nuclei are between 8 and 12 nm apart along the [001] direction, can vary by three orders of magnitude, from 1/s to 1/ms. This work is published in Physical Review B.

We have studied the effect of spin-orbit interaction in a single and double dot. Specially, we derived a generalized form of the Electric Dipole Spin Resonance (EDSR) Hamiltonian for a single spin in an elliptic quantum dot (QD) subject to an arbitrary (in both direction and magnitude) applied magnetic field. We predict a nonlinear behavior of the Rabi frequency as a function of the magnetic field for sufficiently large Zeeman energies, which can alternatively be interpreted as the magnetic field dependence of the g-factor of the confined electron. Similarly, we also explored an EDSR scheme for two spins confined in a double quantum dot (DQD), where coherent Rabi oscillations between the singlet and triplet states are induced by jittering the inter-dot distance at the resonance frequency. The resulting two-electron EDSR can be employed to implement swap gates between two localized spins. Finally, we study different spin relaxation channels of the two electrons due to the phonon emission, for both in-plane and perpendicular magnetic fields. Our results have immediate applications to current EDSR experiments on nanowire QDs, g-factor optimization of confined electrons, and spin decay measurements in DQD spin-orbit qubits. This work is published in Physical Review B.

We have calculated decoherence of two-electron spin states induced by hyperfine interaction with nuclear spins in a double quantum dot with a finite exchange splitting. In particular, we derived an effective pure dephasing Hamiltonian, which is valid when the hyperfine-induced mixing is suppressed due to the relatively large J and the external magnetic field. Using both a quantum theory based on resummation of ring diagrams and semiclassical methods, we identified the dominant dephasing processes in regimes defined by values of the external magnetic field, the singlet-triplet splitting, and inhomogeneity in the total effective magnetic field. We addressed both free induction and Hahn echo decay of superposition of singlet and unpolarized triplet states (both cases are relevant for singlet-triplet qubits realized in double quantum dots). We also studied hyperfine-induced exchange gate errors for two single-spin qubits. Results for III-V semiconductors as well as silicon-based quantum dots were obtained. This work is published in Physical Review B.

We have studied electron-phonon interaction induced decoherence between two-electron singlet and triplet states ina semiconductor double quantum dot using a spin-boson model. We investigated the onset and time evolution of this dephasing, and studied its dependence on quantum dot parameters such as dot size and double dot separations, as well as the host materials (GaAs and Si). At the short time limit, electron-phonon interaction only causes an incomplete initial Gaussian decay of the off-diagonal density matrix element in the singlet-triplet Hilbert space; a complete long-time exponential decay due to phonon relaxation would eventually dominate over two-spin decoherence. We analyzed two-spin decoherence in both symmetric and biased double quantum dots, identifying their difference in electron-phonon coupling and the relevant consequences. This work is published in Physical Review B.

In collaboration with Professor Guy Ramon of Santa Clara University, we have studied the effects of a nearby two-level charge fluctuator on a double-dot two-spin singlet-triplet qubit. Assuming no direct tunneling between the charge fluctuator and the qubit quantum dots, the Coulomb couplings between the qubit and the fluctuator are calculated up to quadrupole-quadrupole order in a multipole expansion. Our results show that the charge environment can severely impact the performance of spin qubits, and indicate working points at which this decoherence channel is minimized. Our analysis also suggests that an ancillary double-dot can potentially help provide regimes for reliable single-qubit operations and idle positions. This work is published in Physical Review B.

2. We have started exploring issues in on-chip or longer-distance communication for spin qubits. In particular, we have studied spin relaxation in a moving quantum dot, and explored the coupling strength between a spin qubit and a microwave cavity.

In one project we have studied decoherence of an electron spin qubit that is being transported in a moving quantum dot. We focused on spin decoherence due to spin-orbit interaction and a random electric potential. We found that at the lowest order, the motion induces longitudinal spin relaxation, with a rate linear in the dot velocity. Our calculated spin relaxation time ranges from sub microseconds in GaAs to above milliseconds in Si, making this relaxation a significant decoherence channel. Our results also give clear indications on how to reduce the decoherence effect of electron motion. This work is published in Physical Review B.

We have also studied transporting spin information by converting it to photons. In particular, we studied a spin-photon coupling scheme using a single electron spin confined in a double quantum dot located in a superconducting stripline cavity. With an external magnetic field, we show that either a spin-orbit interaction (for InAs) or an inhomogeneous magnetic field (for Si and GaAs) could produce a strong spin-photon coupling, with a coupling strength of the order of 1 MHz. With an isotopically purified Si double dot, which has a very long spin coherence time for the electron, it is possible to reach the strong-coupling limit between the spin and the cavity photon, as in cavity quantum electrodynamics. The coupling strength and relaxation rates are calculated based on parameters of existing devices, making this proposal experimentally feasible. This work is published in Physical Review B.

3. We have studied several issues related to qubit design, control, and manipulation. In particular, we studied quantum state transfer in a triple quantum dot, designed a three-spin double dot hybrid qubit and a valley state based charge qubit, and explored how valley splitting in Si can be modified by surface roughness or applied electric field.

In one of the projects, we have explored the non-adiabatic implementation of a quantum teleportation protocol, finding that perfect fidelity can be achieved through resonance. We clarify the physical mechanisms of the teleportation by mapping its dynamics onto two parallel and mutually coherent adiabatic passage channels. By transforming into the adiabatic frame, we explain the resonance through an analogy with the magnetic resonance of a spin-1 particle. Our results establish a fast and robust method for transferring quantum states, and suggest a possible route toward precise and robust quantum gates. This work is published in Physical Review A.

In collaboration with the Wisconsin group led by Mark Eriksson and Sue Coppersmith, but particularly with John Gamble, Mark Friesen, and Sue Coppersmith, we have studied a new hybrid qubit encoding design that involves three electrons in a double dot. This qubit design can be completely controlled electrically, similar to the three-spin in three dot design originally proposed by DiVincenzo and colleagues. We have investigated dephasing of this qubit induced by electron-phonon coupling and by charge noise for pure orbital excitations in GaAs and Si, as well as for pure valley excitations in Si. In GaAs, polar optical phonons give rise to the most important contribution, leading to a typical dephasing rate of 6 GHz. For Si, intervalley optical phonons lead to a typical dephasing rate of 100 kHz for orbital excitations and 1 MHz for valley excitations. For harmonic, disorder-free quantum dots, charge noise is highly suppressed for both orbital and valley excitations. However, both anharmonicity and disorder break the symmetry of the system, which can lead to increased dipole moments and therefore faster dephasing rates. These works are published in Physical Review Letters and in Physical Review B.

In collaboration with Dr. Dimi Culcer and Professor Sankar Das Sarma of University of Maryland, we have devised a platform for noise-resistant quantum computing using the valley degree of freedom of Si quantum dots. The qubit is encoded in two polarized (1,1) spin-triplet states with different valley compositions in a double quantum dot, with a Zeeman field enabling unambiguous initialization. A top gate gives a difference in the valley splitting between the dots, allowing controllable interdot tunneling between opposite valley eigenstates, which enables one-qubit rotations. Two qubit operations rely on a stripline resonator, and readout on charge sensing. Sensitivity to charge and spin fluctuations is determined by intervalley processes and is greatly reduced as compared to conventional charge qubits. In essence, this is a charge qubit scheme that is insensitive to charge noise. This work is published in Physical Review Letters.

In collaboration with Dr. Dimi Culcer and Professor Sankar Das Sarma of University of Maryland, we have studied the effects of interface roughness on valley orbit coupling, valley splitting, and electron state mixing. In particular, we show that (i) variations in the position of the interface, which are expected to occur on a length scale comparable to the lattice constant, affect the magnitude of the valley-orbit coupling; (ii) variations in the size of the potential step at the interface also affect the magnitude of the valley-orbit coupling, and induce transitions between different valley eigenstates; and (iii) if the random positions of the interface is correlated over distances on the order of a quantum dot, which is unlikely but possible, the phase of the valley-orbit coupling could be different in adjacent dots. This work is published in Physical Review B.

In collaboration with Professor B. Koiller and her student Dr A. Saraiva, Dr. M.J. Calderon of University of Madrid, and Professor S. Das Sarma of University of Maryland, we have studied the effect of an applied electric field on the valley splitting of a single confined electron at a Si-SiO2 interface using an effective mass approach. We found that large valley splitting in the order of 10 meV is possible in principle for a smooth interface. This work is published in Physical Review B.

Technology Transfer